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NEW DEVELOPMENTS IN WELDED FABRICATION OF LARGE SOLID-FUEL ROCKET-MOTOR CASES

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NEW DEVELOPMENTS IN WELDED FABRICATION OF LARGE SOLID-FUEL ROCKET-MOTOR CASES

by

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to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
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NEW DEVELOPMENTS IN WELDED FABRICATION OF LARGE SOLID-FUEL ROCKET-MOTOR CASES

SUMMARY

Welding has been an important factor in the successes and failures of large solid-propellant rocket-motor cases. Every large metallic motor case produced has been welded. Quite likely, future metallic chambers also will be welded. The use of welding for this application is logical, since it allows a unique freedom in combining design criteria, material availability and properties, forming capability, and various other manufacturing operations. No scheme has been devised and proven to produce a lightweight, high-strength metallic motor case without welding. Extensive welding-fabrication know-how is required, however, for the successful production of cases. A large number of the early hydrotest failures in motor cases were directly related to the welds. These welds were made by unsatisfactory techniques and were often in unsatisfactory material and designs, or were not given the necessary inspection. Properly made and inspected welds in the proper materials and designs have been and will be a reliable link in motor cases.

Weld fabrication logically involves two distinct items: the welding process and the resulting weldment. The requirements of the weldment in terms of properties, configurations, and dimensional control establish the limitations on the welding process. For motor-case application, the weldment is the case, and these requirements are defined by the designer when he establishes the design for the case. Any limitation that will be applied to a motor case, therefore, must be applied to the welds in the case. For example, a heat treatment that results in excessive shrinkage of the case is of no use in obtaining desired mechanical properties in a weld joint.

The predominant welding processes used in fabricating motor cases are inert-gas-shielded welding and resistance-seam welding. A wide variety of specific process concepts are in use by different fabricators. These variations are not important to success. A much more important fact is that these two processes are probably the most controllable and reliable welding processes available. Selection of specific alloys from the variety of high-strength steels and titanium alloys available also is of minor importance to welding, provided the specific welding requirements of the selected alloy are known and followed.

Three significant conclusions have been drawn relating to welded fabrication of motor cases:

(1) Welding is not currently a limiting factor on the strength levels obtainable in production cases. These cases are being made of high-strength steels heat treated to strength levels between 190,000 and 210,000 uniaxial yield strength.

(2) Welding could be used in motor cases in the near future at the following uniaxial-yield-strength levels:

170,000 psi – Titanium alloys
240,000- 250,000 psi – Low-alloy and hot-work die steels
280,000- 300,000 psi – Coldworked stainless steel* or Mar-Aging steels

(3) Welding may be used in motor cases in 2 to 4 years at the following uniaxial-yield-strength levels:

200,000 psi – Titanium alloys
260,000- 300,000 psi – Low-alloy and hot-work die steels
340,000 psi – Coldworked stainless steel* or Mar-Aging steels

Continued progression to higher strength levels in welded metallic motor cases will not be automatic. Present process controls will require further improvement, although probably not innovations. The general area of defect formation in fusion-weld deposits should be studied to determine the ultimate limitations on welding with available processes. Some of the novel fabrication concepts such as spiral wrapping or high-frequency resistance welding may offer opportunities for significant strength-level increases. Consideration also should be given to such untested techniques as weld strengthening by radiation exposure.

*Provided the special fabrication techniques involved in wrapped cases are sufficiently developed.

INTRODUCTION

Design and fabrication technology of large solid-fuel-rocket motor cases has advanced greatly in the past few years. Much of this improvement can be credited to better materials, to improved welding techniques, and to more thorough and systematic quality control.

This report summarizes the new developments in the welded fabrication of large solid-fuel rocket-motor cases, and updates DMIC Memorandum 56 on this subject. The present report presents background information on the development of welded solid-fuel motor cases, new materials being used or evaluated for possible use, new fabrication concepts, new welding techniques, and a general discussion of design and procedures for welding.

Initially, large rocket-motor cases were fabricated by the roll-and-weld technique. The welded, longitudinal seams produced by this technique fell unfairly in disrepute. Nevertheless, fabricators went to hydrospinning, deep drawing, and machining from forgings to produce cases. Current requirements for very large motor cases are making the roll-and-weld technique attractive once again because of size limitations in forming, machining, and heat-treating facilities. This need for larger diameter cases is affecting the choice of case materials. Materials being favored are those that can be heat treated in flat sheets, rolled into cylinders, welded in the heat-treated condition, and then locally aged to produce the desired mechanical properties in the weld area. The maraging nickel steels and the beta-titanium alloy, Ti-13V-11Cr-3Al, seem to fulfill these requirements. The weldability and weld ductility of these materials in the aged condition are suspect. Extensive research is being conducted on these materials.

The low-alloy hardenable steels, such as Ladish D-6ac, AISI4340, and AMS 6434, are still the most widely used, particularly D-6ac. However, titanium alloys such as Ti-6Al-4V are replacing steel in some applications. Strength-to-density ratios exceeding 1×10^6 inches in some of the alloys, notably Ti-13V-11Cr-3Al, are the biggest attraction of the titanium alloys.

The cold-worked stainless steels have been used principally for novel design and fabrication concepts such as the spiral-wrapped, foil-gage cases. Although subscale and, in some instances, full-scale cases have recorded very high burst strengths, these novel concepts have not been adopted for production cases.

The electron-beam welding process has received considerable attention by fabricators and research and development organizations. This process offers many advantages for joining hard-to-weld materials with high-quality welds. Thus far, it has not been possible to use these advantages except on small-part weldments because existing electron-beam welding chambers are too small. Chambers large enough to accommodate full-size motor cases have been considered and, reportedly, are being built.

Other processes, such as high-frequency resistance welding, offer great promise for motor-case construction, particularly for large-diameter cases. Work is being planned toward this objective. Nevertheless, the inert-gas, tungsten-arc welding process still is preferred for conventional motor-case fabrication. The improved reliability of cases welded with this process are, at least partly, the result of better appreciation and control of the welding variables and of improved inspection techniques.

Despite appreciable advances in welded fabrication of motor cases, extensive research and development is needed. The investigations of new materials, new welding processes, and new design concepts must be merged into a practical end product. The need for cases with ever-larger diameters makes the need for such continued investigation vital.

BACKGROUND INFORMATION

Considerable change has occurred in the design and fabrication techniques used to produce large solid-fuel, rocket-motor cases. Initially, these cases were fabricated by the roll-and-weld technique (Figure 1a). In this process, flat sheets are rolled into cylinders, and the longitudinal seams are welded. The cylindrical sections then are joined to each other and to the end closures by welding the girth or circumferential seam. This technique was used initially to fabricate first- and second-stage Polaris cases. The longitudinal weld was blamed for many of the hydrotest failures of these cases. Extensive examinations of failed cases showed that most of the failures resulted from either poor welding techniques or inadequate inspection coupled with poor fracture toughness of the steel at the high strength level.

Nevertheless, considerable effort was directed toward eliminating the longitudinal seam from future cases (Figure 1b). Cylindrical case sections were formed by spinning, deep drawing, and by machining ring forgings. Other techniques such as spiral wrapping and stretch forming at cryogenic temperatures have been and still are being evaluated. Although the reliability of welded cases has increased markedly, most of the improvement can be ascribed to better control of materials and processing. Douglas Aircraft[(1)*] credits better design and material testing concepts along with meticulous quality control for the marked improvement in reliability of solid-fuel motor cases. This improvement is shown graphically in Figure 2. It is significant that all these cases were fabricated by the roll-and-weld technique – a further indication that longitudinal seams, per se, are not necessarily objectionable provided high standards of material and fabrication techniques are maintained.

The popularity of the roll-and-weld technique is rising sharply. This resurgence is being brought about principally for one reason – case size. Previously, the largest solid-fuel motor case was about 66 inches in diameter (Minuteman first stage). Now, cases are being considered up to 240 inches in diameter. Limitations in forming, heat treating, and machining facilities are forcing manufacturers to reconsider the roll-and-weld technique.

So, basic case design has come full circle from longitudinally-seamed cases to seamless cases and back again. However, in negotiating this circle, valuable experience and an appreciation of the necessary quality controls have been gained. The balance of this report will outline much of this experience.

*References are listed on page 25.

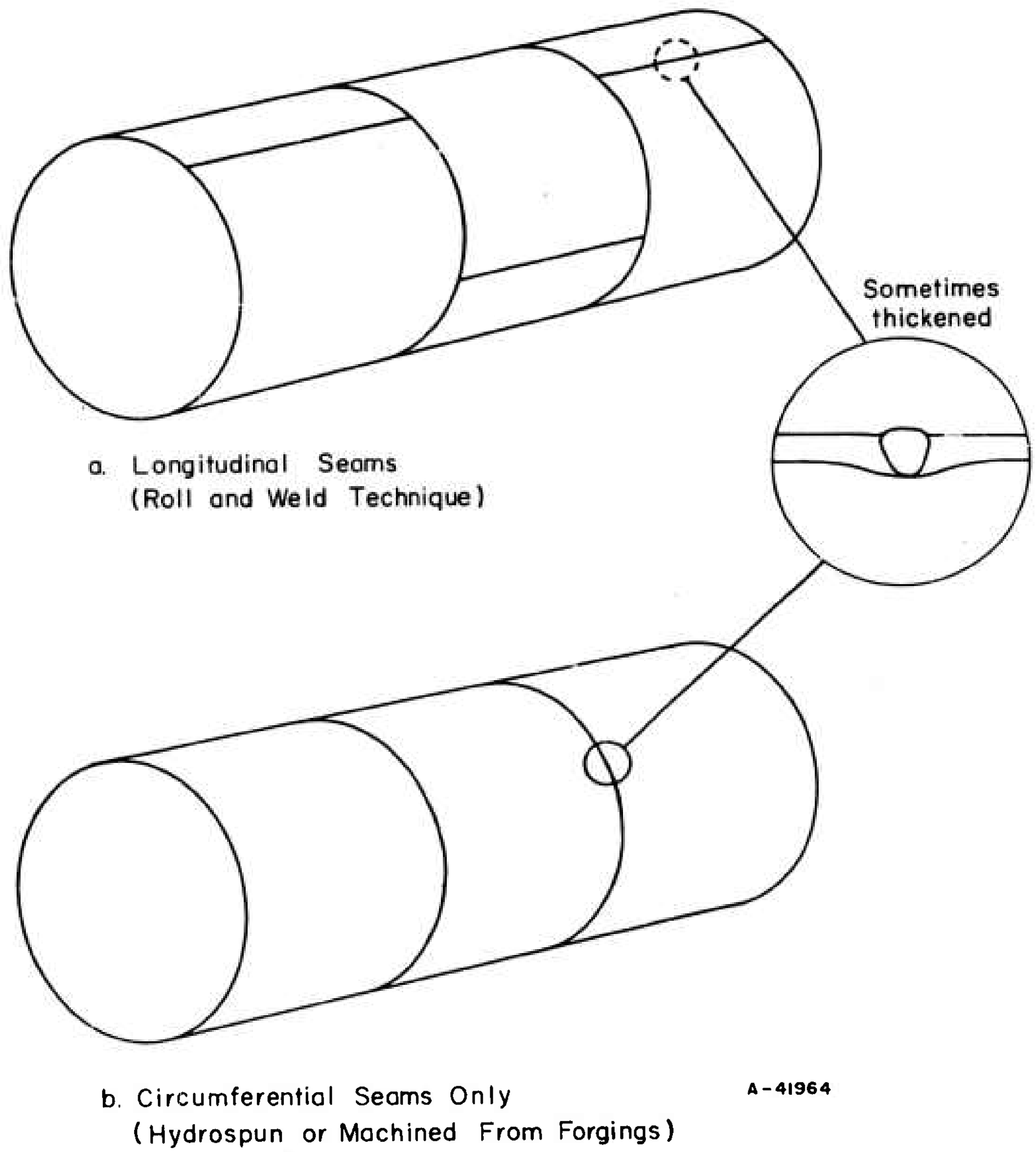


FIGURE 1. PRODUCTION MOTOR-CASE WELDING CONFIGURATIONS

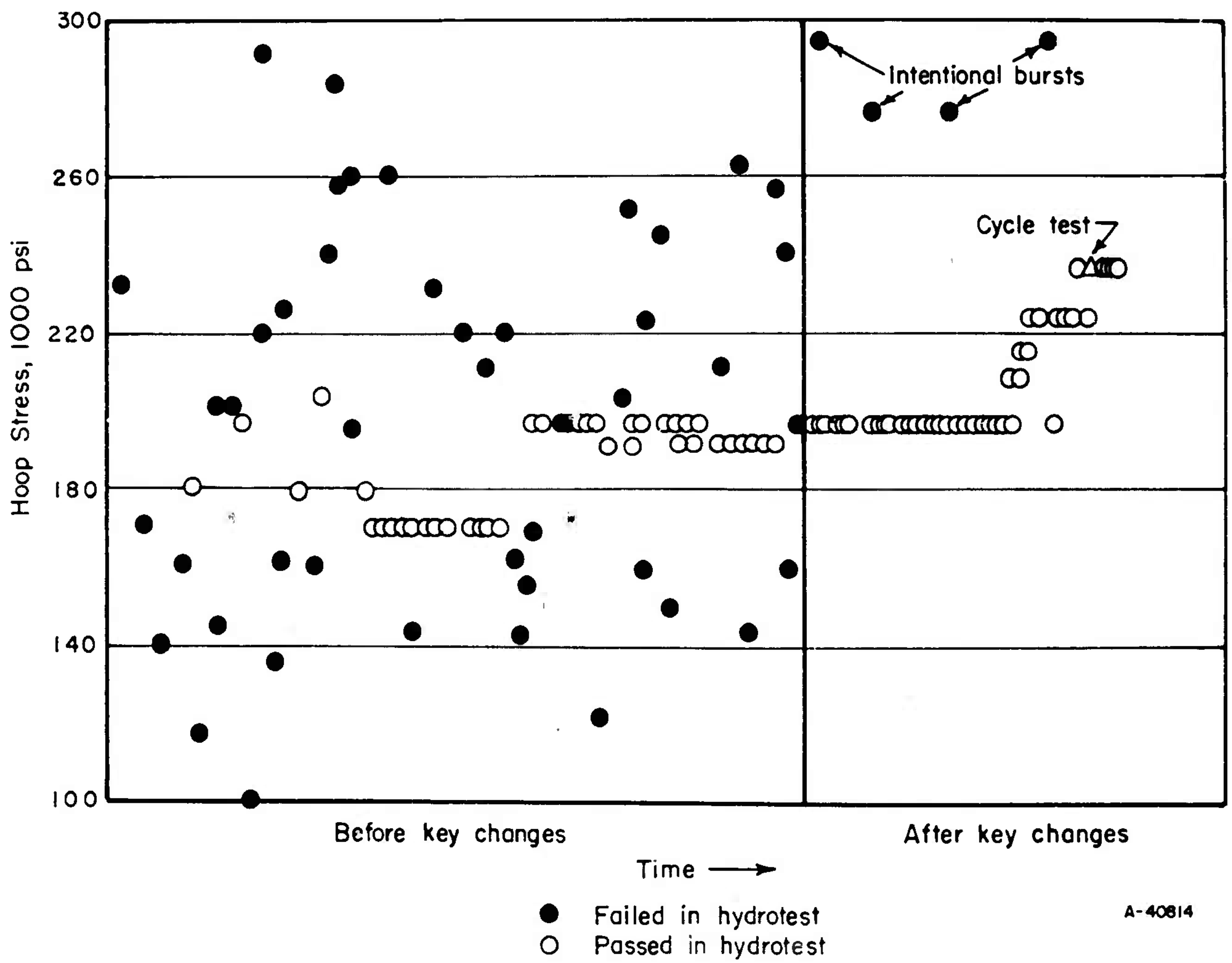


FIGURE 2. RELIABILITY OF SOLID-FUEL ROCKET-MOTOR CASES FROM DOUGLAS AIRCRAFT

MATERIALS FOR LARGE SOLID-FUEL MOTOR CASES

Many steel alloys and some titanium alloys have been used or evaluated for possible use in large solid-fuel motor cases. The steels are classified as (1) low-alloy, hardenable steels, (2) hot-work die steels, (3) cold-worked stainless steels, (4) precipitation-hardenable stainless steels, and (5) Mar-Aging steels. The nominal compositions of these steel and titanium alloys are shown in Table 1. Typical ultimate strengths and strength-density ratios that can be obtained with these alloys are shown in Table 2. There is no one material that is best for use in large solid-fuel motor cases. Selection of the material must be carefully made on the basis of many factors such as availability, cost, and case performance requirements. Welding characteristics are one factor that should influence the material selection. A general discussion of the various groups of alloys that have been studied for motor-case use follows.

Low-Alloy Hardenable Steels

By far the great majority of the large solid-fuel rocket-motor cases have been fabricated of steels of the low-alloy hardenable group. Many of these basically are AISI 4340 steels, modified to produce higher strength and greater hardenability. As shown in Table 2, they can be heat treated to ultimate strengths approaching 300,000 psi. The heat treatments involve austenitizing, quenching to room temperature (air cooling in the case of the high-hardenability materials such as 300-M), and tempering at 600 to 1000 F, depending on desired strength.

All of the materials in this group have been investigated to varying degrees for motor-case materials. Only the AMS 6434, AISI 4340, 300-M, and Ladish D-6ac of this group have been used extensively for actual case production. Polaris A-2 first-stage cases are currently made from AMS 6434. The Ladish D-6ac alloy is used for first- and the Wing I second-stage Minuteman cases. These cases are heat treated to insure a 190,000-psi minimum yield strength. The cylindrical segments of these cases are formed by spinning, flow turning, or machining from ring forgings. The segments are joined by circumferential welds to produce a case. Cases produced in this manner have had a very high reliability. As mentioned earlier, much of this success can be ascribed to better design and quality control and to improved materials. Vacuum-melted material has been preferred by a few vendors over air-melted material because of its smaller inclusions and its lower tramp-element and gas content. It should be pointed out that the lower tramp-element content is a result of better starting materials and not necessarily a result of vacuum melting.

The low-alloy, hardenable steels, in general, have good weldability. However, porosity and weld- and heat-affected-zone cracking have been a problem. These are discussed in a later section of the report under "Defects".

Practically all of the welding processes can be used to join these materials. However, almost all case welding is done automatically by the inert-gas, tungsten-arc (TIG) process with the addition of filler metal. The TIG process is preferred because thin

TABLE 1. NOMINAL COMPOSITIONS OF ALLOYS CONSIDERED FOR LARGE SOLID-FUEL ROCKET-MOTOR CASES

Alloy Designation or Trade Name	Chemical Composition, weight per cent (Ranges Shown Where Available)																				
	C	Mn	Si	Cr	Ni	Mo	V	Co	Cb	Al	Ti	Cu	N	Fe	B	Zr	W	Ca	H	O	Sn
Low-Alloy Hardenable Steels																					
17-22 AS	0.28-0.33	0.45-0.65	0.55-0.75	1.00-1.50	--	0.40-0.60	0.20-0.30	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
AISI 4130	0.28-0.33	0.40-0.60	0.20-0.35	0.80-1.10	--	0.15-0.25	--	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
AMS 6434	0.31-0.38	0.60-0.80	0.20-0.35	0.65-0.90	1.65-2.00	0.30-0.40	0.17-0.23	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
AISI 4340	0.38-0.43	0.60-0.80	0.20-0.35	0.70-0.90	1.65-2.00	0.20-0.30	--	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
Airsteel X-200	0.41-0.46	0.75-1.00	1.40-1.75	1.90-2.25	--	0.45-0.60	0.03-0.08	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
300-M	0.41-0.46	0.65-0.90	1.45-1.80	0.70-0.95	1.65-2.00	0.30-0.45	0.05 min	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
MBMC-1	0.42-0.46	0.70-0.90	1.50-1.70	0.60-0.90	--	--	0.01 min	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
Ladish D-6ac	0.44-0.48	0.60-0.90	0.15-0.30	0.92-1.18	0.40-0.70	0.90-1.10	0.05-0.10	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
Rocoloy 270	0.40-0.45	0.50-0.80	1.00-1.25	1.50-1.80	0.70-1.00	0.30-0.45	0.20-0.30	1.60-1.90	--	--	--	--	--	Balance	--	--	0.30-0.50	--	--	--	--
Hot-Work Die Steels																					
Crucible 56	0.38-0.44	0.40-0.70	0.80-1.20	3.00-3.60	--	2.00-2.70	0.25-0.50	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
Crucible 218	0.40	0.40	1.05	5.00	--	1.35	0.50	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
Potomac A	0.40	0.30	0.90	5.00	--	1.30	0.50	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
Potomac M	0.40	0.30	1.00	5.00	--	1.00	1.00	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
Vascojet 1000	0.40	0.30	0.90	5.00	--	1.30	0.50	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
Cold-Worked Stainless Steels																					
AISI 301	0.15 max	2.00 max	1.00 max	16.0-18.0	6.0-8.0	--	--	--	--	--	--	--	--	Balance	--	--	--	--	--	--	--
JLS-300	0.11	1.27	0.69	17.2	5.1	0.16	--	--	--	--	--	0.15	0.08	Balance	--	--	--	--	--	--	--
AM 350	0.08-0.12	0.50-1.25	0.50 max	16.0-17.0	4.0-5.0	2.5-3.25	--	--	--	--	--	--	0.07-0.13	Balance	--	--	--	--	--	--	--
AM 355	0.10-0.15	0.50-1.25	0.50 max	15.0-16.0	4.0-5.0	2.5-3.25	--	--	--	--	--	--	0.07-0.13	Balance	--	--	--	--	--	--	--
AM 357	0.20-0.25	0.50-1.25	0.50 max	13.5-14.5	4.0-5.0	2.5-3.25	--	--	--	--	--	--	0.07-0.13	Balance	--	--	--	--	--	--	--
Precipitation-Hardenable Stainless Steels																					
PH-12-8-6	0.07	0.50	0.40	11.5	8.0	6.0	--	--	--	1.15	--	--	--	Balance	--	--	--	--	--	--	--
PH-15-7 MO	0.09 max	1.00 max	1.00 max	14.0-16.0	6.50-7.75	2.0-3.0	--	--	--	0.75-1.50	--	--	--	Balance	--	--	--	--	--	--	--
17-7 PH	0.09 max	1.00 max	1.00 max	16.0-18.0	6.50-7.75	--	--	--	--	0.75-1.50	--	--	--	Balance	--	--	--	--	--	--	--
17-4 PH	0.04	0.60	0.40	17.0	4.0	--	--	--	0.3+ Ta	--	--	4.0	--	Balance	--	--	--	--	--	--	--
AM 359	0.17-0.21	0.50-1.25	0.50 max	13.5-14.5	6.50-7.50	2.50-3.00	--	--	--	0.60-1.35	--	--	Low	Balance	--	--	--	--	--	--	--
Mar-Aging Steels																					
18 per cent Ni (250 ksi)	0.03 max	0.10 max	0.10 max	--	17.0-19.0	4.6-5.1	--	7.0-8.0	--	0.05-0.15	0.3-0.5	--	--	Balance	0.003 added	0.02 added	--	0.05 added	--	--	--
18 per cent Ni (300 ksi)	0.03 max	0.10 max	0.10 max	--	18.0-19.0	4.6-5.2	--	8.5-9.5	--	0.10 added	0.5-0.8	--	--	Balance	0.003 added	0.02 added	--	0.05 added	--	--	--
20 per cent Ni	0.03 max	0.15 max	0.15 max	--	18.0-20.0	--	--	--	0.3-0.6	0.15-0.35	1.3-1.6	--	--	Balance	0.003 added	0.02 added	--	0.05 added	--	--	--
25 per cent Ni	0.03 max	0.15 max	0.15 max	--	25.0-26.0	--	--	--	0.3-0.6	0.15-0.35	1.3-1.6	--	--	Balance	0.003 added	0.02 added	--	0.05 added	--	--	--
Titanium																					
-6Al-4V	0.10 max	--	--	--	--	--	3.5-4.5	--	--	5.5-6.75	Balance	--	0.07 max	0.04 max	--	--	--	--	0.015 max	0.030 max	--
-13V-11Cr-3Al (Typical)	0.024	--	--	--	--	--	13.4	--	--	2.8	Balance	--	0.023	0.19	--	--	--	--	0.019	0.133	--
-6Al-6V-2Sn	0.02	--	--	--	--	--	5.38	--	--	5.73	Balance	0.76	0.014	0.87	--	--	--	--	0.010	0.137	2.30

TABLE 2. TYPICAL PROPERTIES OF ALLOYS CONSIDERED FOR SOLID-FUEL ROCKET-MOTOR CASES

Alloy Designation or Trade Name	Condition	Typical Ultimate Strength, ksi	Density, pounds per cubic inch	Strength-Density Ratio, 10^6 inches
Low-Alloy Hardenable Steels				
17-22AS	Quenched and tempered	220	0.283	0.78
AISI 4130	Ditto	235	0.283	0.83
AMS 6434	"	265	0.28(?)	0.95
AISI 4340	"	265	0.283	0.94
Airsteel X-200	"	290	0.278	1.04
300-M	"	290	0.278	1.04
MBMC-1	"	280 (min)	0.28(?)	1.00 (min)
Ladish D-6ac	"	275	0.283	0.97
Rocoloy 270	"	320	0.28(?)	1.14
Hot-Work Die Steels (H-11 Type)				
Crucible 56	Quenched and tempered	280	0.281	1.00
Crucible 218	Ditto	280	0.281	1.00
Potomac A	"	280	0.281	1.00
Potomac M	"	280	0.281	1.00
Vascojet 1000	"	280	0.281	1.00
Cold-Worked Stainless Steels				
AISI 301	Cold stretching	280	0.286	0.98
JLS-300	CRT	345	0.286	1.21
AM 350	CRT	225	0.282	0.80
AM 355	SCCRT	295	0.282	1.05
AM 357	SCCRT	320	0.286	1.12
Precipitation-Hardenable Stainless Steels				
PH-12-8-6	T-25MH	300	0.282	1.17
PH 15-7 Mo	CH900 (cold rolled, aged)	265	0.277	0.96
17-7 PH	CH900	265	0.276	0.96
17-4 PH	H900	195	0.281	0.69
AM 359		250	0.286	0.875
Mar-Aging Steels				
18 per cent Ni	Maraged	250	0.289	0.87
20 per cent Ni	Ditto	275	0.286	0.95
25 per cent Ni	"	275	0.286	0.95
18 per cent Ni	"	300	0.289	1.04
Titanium				
6Al-4V	Solution treat, age	175	0.160	1.10
13V-11Cr-3Al	Ditto	200	0.175	1.14
6Al-6V-2Sn	"	215	0.161	1.34

materials (0.080 to 0.250 inch) are being joined. As case size and case thickness are increased, the inert-gas, consumable-electrode (MIG) process will be used to a much greater extent. Details of welding procedures will be discussed in later sections.

Hot-Work Die Steels

The hot-work die steels have been of interest to rocket-motor-case fabricators because of their high strengths (240,000 and 290,000-psi yield and ultimate strengths, respectively), high hardenability, and high tempering temperatures (about 1000 F). However, only the H-11-type alloy (5 Cr) has been used to any appreciable extent. Pratt & Whitney Aircraft fabricated both first- and second-stage Pershing cases from this alloy. Solar Aircraft fabricated Minuteman first-stage developmental cases of both air-melted and vacuum-melted H-11 alloy with good success. These cases were heat treated to 200,000-psi yield strength.

The weldability of the hot-work die steels is comparable to that of the low-alloy hardenable steels.

Cold-Worked Stainless Steels

Alloys of this group were developed to obtain their strength by cold work or by cold work plus aging. These materials are austenitic in the annealed condition but readily respond to strain hardening and strain-induced martensitic transformation to produce yield and ultimate strengths exceeding 300,000 psi. They have been used almost exclusively in development programs for unconventional motor-case designs such as the wrapped cases fabricated by Budd[2] and Ryan[3] or for unconventional forming such as the developmental subscale cases fabricated by Arde-Portland[4]. The Budd and Ryan cases were fabricated from cold-reduced AM 355 steel in the SCCRT (subzero-cooled, cold-rolled, and tempered) condition in foil gage. These cases were arc and resistance welded in this hardened condition. The Arde-Portland subscale cases were fabricated of AISI 301 stainless steel by the roll-and-weld technique. The welded cases were expanded hydrostatically at cryogenic temperatures to obtain the work hardening necessary to develop strength. These unconventional cases will be discussed in more detail in a later section.

The steels in this group can be welded by most of the conventional welding processes. Again, the inert-gas-shielded processes are preferred. Welding is done on annealed material where possible. However, the wrapped cases, fabricated of cold-rolled sheet, are welded in the fully hardened condition. The welds and heat-affected zones, then, are in the low-strength, annealed condition after welding. Reinforcing plates or thickened joints have been used to redistribute the load around these low-strength areas. Localized heat treatments may be used for those materials that will respond to an aging treatment.

Precipitation-Hardenable Stainless Steels

The steels of this group have been investigated and used extensively by the aircraft industry but have not been used to any appreciable extent for case fabrication. These steels are characterized by relatively high strengths and by good resistance to general corrosion. However, at the higher strength levels they may be susceptible to stress corrosion. They can be welded by most of the welding processes, but the inert-gas-consumable- and nonconsumable-electrode processes are preferred. The AM 359 alloy is a modification of the cold-rolled stainless grades such as AM 350, AM 355, and AM 357, but it contains sufficient aluminum to develop the true precipitation-hardening effect. Cold rolling is not recommended for this alloy.

Mar-Aging Nickel Steels

One of the most interesting and promising groups of steels considered for rocket-motor cases are the Mar-Aging nickel steels, developed by International Nickel Company. The three basic alloys of this group contain 18, 20, and 25 per cent nickel. The materials attain very high strengths by simple heat treatments which do not involve a quench. The 18 and 20 per cent nickel steels are martensitic in the annealed condition, whereas the 25 per cent nickel steel is partially austenitic in the annealed condition. Full strength can be attained by "maraging" at 900 F for 3 hours for the 18 per cent nickel steel and at 900 F for 1 hour for the 20 per cent nickel steel. Direct aging of the 18 and 20 per cent nickel steels without an intermediate anneal is possible when suitable control over the hot-work finishing temperature is provided. A 1500 F anneal after hot work is recommended for the 25 per cent nickel steels. Hardening is accomplished by either of the following treatments:

(1) Anneal at 1500 F, soak for 1 hour per inch of thickness, air cool; heat to 1300 F, soak 4 hours, air cool; refrigerate at -100 F for several hours (this step may be eliminated when the titanium content is near the upper side of the range); age at 800 to 900 F for 1 to 4 hours, air cool.

(2) Anneal at 1500 F (same time as above), air cool; cold work (25 per cent reduction or more); refrigerate at - 100 F; age at 800 to 900 F, 1 to 4 hours, air cool.

The strengths of the steels containing 18 and 20 per cent nickel can be increased considerably by cold working prior to maraging, as shown by International Nickel Company data for steel bars:(5)

Alloy (Bar Form)	Treatment	Room-Temperature Tensile Properties: 0.2 Per Cent Offset Yield Strength, ksi	Ultimate Strength, ksi	Elongation in 1 Inch, per cent	Reduction of Area, per cent
18 Nickel[a]	Maraged	238	241	12	58
Ditto[a]	Maraged + 50 per cent cold work	247	250	14	58
20 Nickel	Maraged	246	256	11	46
Ditto	Maraged + 50 per cent cold work	263	268	12	57

(a) The strengths are slightly below normal for this material because the Co, Mo, and Ti contents are at or below the minimum desired composition.

The strengths of these alloys in sheet form are higher than those shown for bar material in the tabulation above. More detailed information on the Mar-Aging steels may be found in DMIC Memorandum 156.

The Budd Company[6] has investigated the 20 and 25 per cent nickel steels. It favors the 20 per cent nickel steel because of consistently higher strengths in the cold-rolled and aged condition than are obtained with the 25 per cent nickel steel in the same condition. So, Budd has eliminated the 25 per cent nickel steel from its evaluation program. It is currently studying the weldability of the 20 per cent nickel steel. Thus far, automatic TIG welding has been used on this alloy in 0.032- and in 0.075-inch-thick sheet in both the cold-rolled and the annealed-and-aged conditions. Filler wires of matching composition were used. Budd found that heat input, restraint, and shielding are very important. Weld cracking occurred if the heat input was too high and the chilling (weld cooling) too drastic. Also, it was found that high restraint promoted weld-center-line cracking. Adequate shielding with argon and helium was found to be very important because of the high titanium and aluminum contents of these alloys.

International Nickel Company[5] reports that all three alloys can be welded manually with coated electrodes or by the inert-gas-shielded process. Preheating reportedly is not required even when welding hardened material. Localized postweld aging at 850 to 900 F is required to restore strength to the weld and heat-affected zone. Curtiss-Wright[7] is currently investigating these alloys and plans welding evaluations.

Welding data on the Mar-Aging steels is too limited to establish the behavior of these materials in rocket-motor cases. As additional information is obtained, the suitability of Mar-Aging steels for this application will be determined.

Titanium Alloys

Some of the titanium alloys have been particularly appealing to fabricators of rocket-motor cases because of the high strength-to-weight ratios of the alloys. The alpha-beta alloys have been investigated extensively for this application. The mechanical properties of this group of alloys may be altered greatly by heat treatment. Ductility is greatly influenced by microstructure. As a result, welded joints in most of the alpha-beta alloys are too brittle to be useful. One notable exception is the Ti-6Al-4V alloy.

This alloy has been used with success for Polaris second-stage and Minuteman second- and third-stage cases. The cylindrical sections were produced by machining forgings and by hydrospinning. The sections were joined together by circumferential welds deposited by the inert-gas tungsten-arc (TIG) process with the addition of filler metal. Both commercially pure (alpha type) and Ti-6Al-4V filler compositions have been used. The case components were welded in the annealed condition. The completed cases were solution treated and aged. The weld joint areas were thickened to compensate for lower weld-metal strength.

Another titanium alloy that has been of considerable interest is the beta-alloy, Ti-13V-11Cr-3Al (also called B120 VCA). Potentially it has one of the highest strength-density ratios of any metallic material used for rocket-motor cases. One distinct advantage of this alloy is that the desired mechanical properties can be obtained without quenching from high temperatures. This alloy may be purchased in the solution-annealed (solution-treated) condition and then strengthened by a simple aging treatment at temperatures between 800 and 900 F. Actual welding of this alloy is not difficult. Arc-welded joints are very ductile in the as-welded condition but are weak, as expected for essentially annealed material. Weldment strength can be increased considerably by aging, but only at a sacrifice in ductility. Many of the welding investigations on this alloy have been directed toward improving weld ductility in the aged condition. Budd[(8)] is evaluating welds in this alloy made by the high-voltage electron-beam and by the TIG welding processes. Their data, thus far, indicate that reaging of electron-beam-welded specimens made from cold-rolled and aged material can produce high strengths with measurable ductility. Pratt & Whitney[(9)] also is investigating the beta alloy for solid-fuel motor cases. The weld-development phase of their research is aimed primarily at the improvement of weld quality and fracture toughness. Both electron-beam (high-voltage type) and TIG welding processes are being used. Filler wires evaluated for TIG welding include commercially pure titanium and the beta alloy. Budd has studied tensile (notched and unnotched), bend, and fracture toughness properties of the welds and heat-affected zones under a wide variety of welding conditions. However, these evaluations are of weldments in the as-welded condition. Thus far, Budd has concluded that the electron-beam welding produces slight improvement in notched tensile strength and fracture toughness over that obtained with TIG welding. Budd also shows that multipass (as compared with single pass) TIG welding reduces grain size and improves bend ductility without improving notched tensile strength or fracture toughness.

Some of the details concerning welding procedures are discussed in later sections of this report. However, a more complete discussion of procedures for welding titanium and its alloys is available in DMIC Report 122, "The Welding of Titanium and Titanium Alloys".

NEW FABRICATION CONCEPTS

The brief, chronological account of the development of large solid-fuel rocket-motor cases given in the section entitled "Background Information" pointed out the efforts made to eliminate the roll-and-weld technique of case fabrication. While most development and production contracts shifted to hydrospinning or to machining forgings, efforts were made to develop entirely new fabrication concepts. These new concepts were aimed

primarily at one objective – elimination of finished-case heat treatment. The exacting dimensional control required for large motor cases is difficult to maintain when a full-size case is quenched or air cooled from temperatures of 1600 to 1800 F. If cases could be fabricated from fully-hardened material or hardened by cold work after fabrication, the problem of dimension control during heat treating could be eliminated. This is the basic philosophy of the novel fabrication techniques tried by Ryan[3], Budd[2], and Arde-Portland[4](Figure 3). The Ryan Wrap concept consisted of spirally wrapping, on a mandrel, strips of very thin (about 8 mils thick) AM 355 SCCRT stainless steel that had been cold worked about 70 per cent. AM 355 has yield and ultimate strengths exceeding 300,000 psi in the SCCRT condition. End closures were fitted on the mandrel so that the spiral wraps would overlap a portion of the closure. Resistance spot welding was used to join the overlapped spiral wrap to each other and to the end closure. The finished case contained 8 layers. A full-sized Polaris second-stage case, fabricated by this technique, was tested hydrostatically to failure. This case failed at a nominal stress of 290,000 psi. However, the Ryan Wrap process has not been adopted for production contracts.

The Budd concept was similar. Budd produced subscale cases by rolling 0.014-inch-thick AM 355 SCCRT stainless steel sheets and strips into cylinders. When sheets were used, the longitudinal joint was made by resistance spot welding in a "chevron" or "saw-tooth" pattern. The number of layers varied from one to three depending on load requirements and thickness of materials. Contoured heads were resistance spot and fusion welded to the cylindrical section, using reinforcing plates or doublers for weld reinforcement. The nominal stresses at failure during hydrostatic testing of subscale cases ranged from 232,500 to 296,000 psi for various designs tested.

Following these early successes, Budd began an extensive program of material selection and evaluation. The materials chosen for further consideration were the 20 per cent nickel steel and the beta-titanium alloy, Ti-13V-11Cr-3Al. These materials were favored because (1) they have strength-density ratios exceeding 1×10^6 inch, (2) they are both weldable by TIG, electron-beam, and resistance-spot welding, (3) they possess sufficient "as-welded" strength or can develop this strength by moderate-temperature postwelding heat treatments, (4) heat treatments are simple, consisting of a single aging treatment for the titanium alloy and a subzero cool and aging treatment for the 20 per cent nickel steel, (5) both materials are relatively stable dimensionally when heat treated because there are no phase transformations, and (6) both materials are commercially available as sheet or strip in coil lengths.

During the course of this investigation the wrapped-case concept was abandoned in favor of a cylindrical section formed from single-thickness strip and having a preferentially oriented helical butt weld. Five reasons were given for this basic design modification: (1) the penalties imposed by discontinuities resulting from lap joints or doubler reinforcements are reduced, (2) the connection of the head to the cylindrical section is simplified by eliminating the necessity of joining a multilayer section to the head, (3) preferential orientation of the weld line reduces the normal stress across the weld line, (4) weld strength can be improved either by mechanical means or by a mild aging heat treatment, and (5) proven and available process techniques can be employed in the fabrication of this design of cylindrical section. Budd plans to fabricate and test 20-inch-diameter subscale cases fabricated by this technique.

The Arde-Portland concept consists of fabricating an undersize pressure vessel, such as a rocket-motor case, from work-hardenable material with the material in the annealed condition. The undersized case then is stretched, at cryogenic temperatures, to the full size required. The cryogenic stretching operation produces high strength in the entire case including end closure, flanges, and all welds. Subscale cases 12 inches in diameter have been fabricated of AISI 301, columbium-modified 301, and AM 355 stainless steels. However, most of the cases have been fabricated from the AISI 301 stainless steel. Cases about 0.060-inch thick were fabricated by the roll-and-weld technique. The longitudinal and circumferential joints were welded in a single pass with the automatic TIG process. Filler metals were added, but the types of filler wire were not disclosed. The cases were stretched at -320 F by hydrostatic pressure. Some of the cases were expanded "free" so that the cylindrical sections tended to "barrel out". Expansion against a die produced uniform cylinders. Cases fabricated of AISI 301 stainless steel and work hardened by the Arde-Portland "Ardeform" process have attained nominal burst strengths of 280,000 psi. Arde-Portland conclude the following: (1) It is feasible and practical to manufacture rocket-motor cases by this technique, (2) cryogenically stretch-formed material exhibits notched-unnotched tensile strength ratios of 1.0 or greater up to a yield strength of 270,000 psi, (3) dimensions of the cylindrical portion of the case can be controlled accurately by stretching in a die, and (4) large bosses can be stretched integrally with end closures.

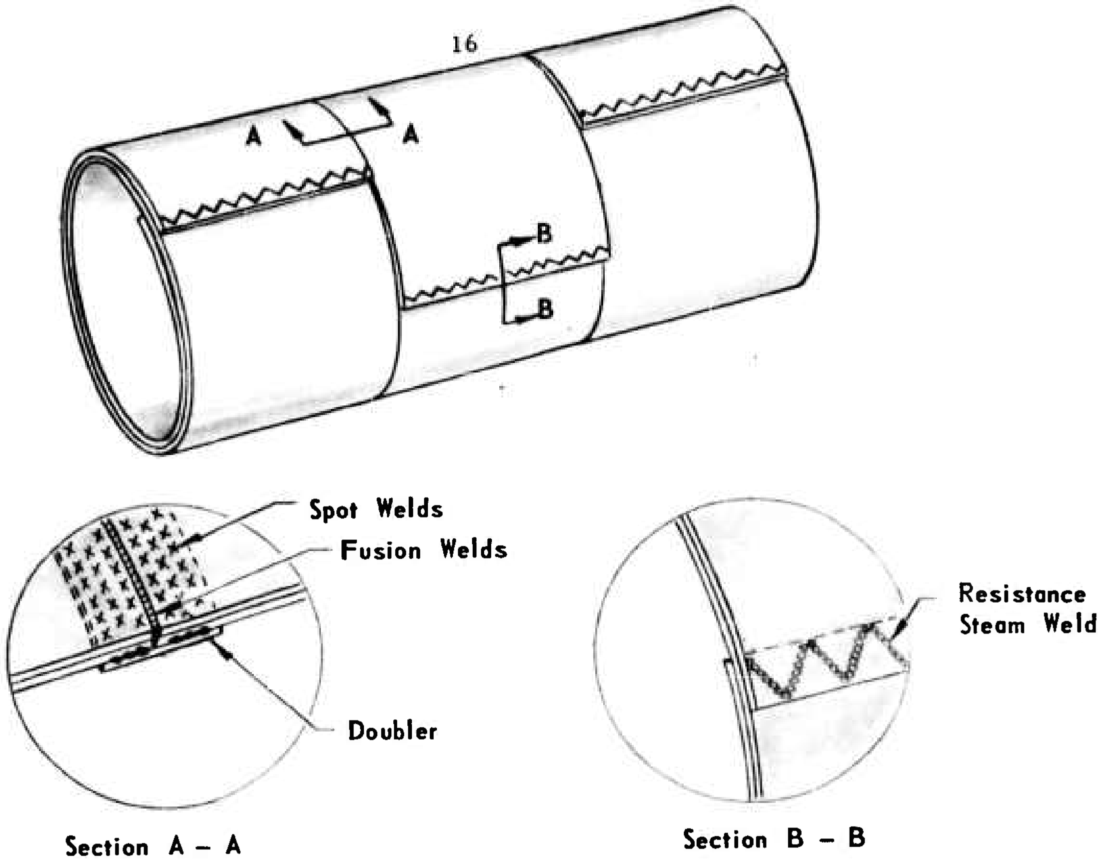
These novel design and fabrication concepts offer promise for high-strength, lightweight cases of current size. However, as case diameters increase to around 160 inches and larger, it seems likely that the preferred fabrication technique will be the roll-and-weld concept using relatively thick plates heat treated prior to roll forming.

NEW WELDING TECHNIQUES

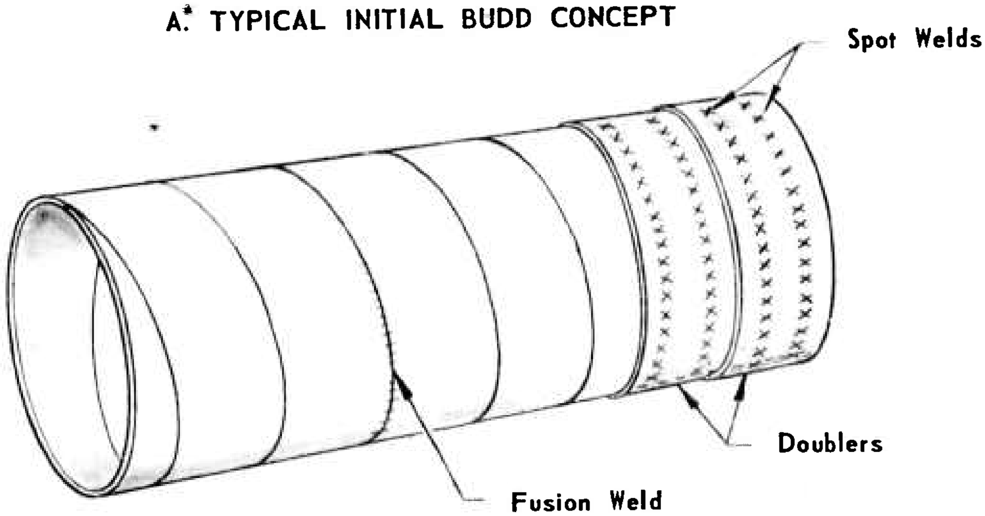
The inert-gas tungsten-arc (TIG) process remains the preferred welding process for the fabrication of large thin-walled rocket-motor cases. However, the relatively new electron-beam welding process is receiving considerable attention by fabricators. This process was described in DMIC Report 131, "New Developments in the Welding of Metals". Briefly, the parts to be joined are bombarded by a stream of high-energy electrons in a vacuum. As the electron stream hits the workpieces, most of the energy of the electrons is given up as heat. By concentrating the beam on a small area, sufficient heat is generated to melt the edges of the workpieces and produce a weld.

The electrons are accelerated toward the workpiece by the voltage applied between a filament and the workpiece or an anode placed between the filament and the workpiece. The energy imparted to the electrons, and subsequently appearing as heat in the workpiece, is largely determined by the applied voltage. Electron-beam welders are available with voltage ratings ranging from 5 to 150 kilovolts. Actually, the commercially available welders generally are classed as low-voltage type (below about 30 kilovolts) and high-voltage type (up to about 150 kilovolts).

The advantages of electron-beam welding are that (1) welding is done at high vacuum so that weld-metal contamination from external sources is virtually eliminated,

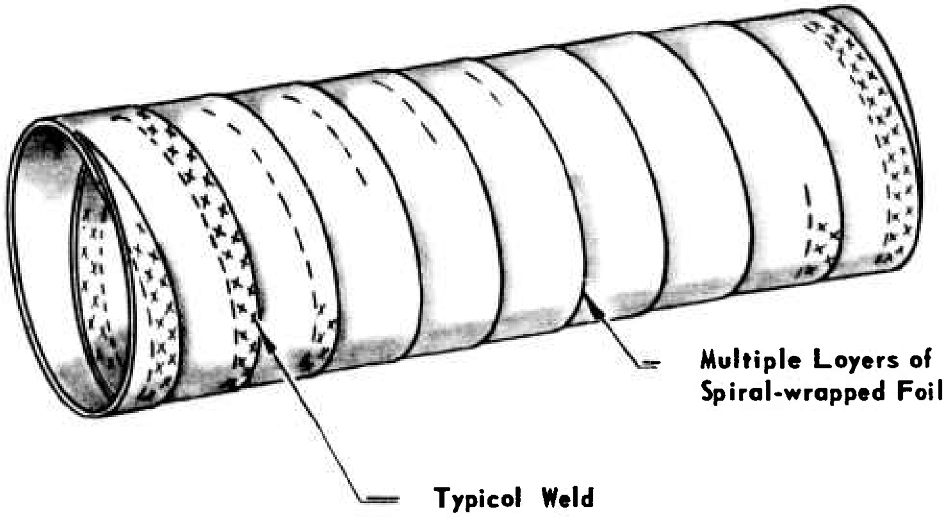


A.* TYPICAL INITIAL BUDD CONCEPT

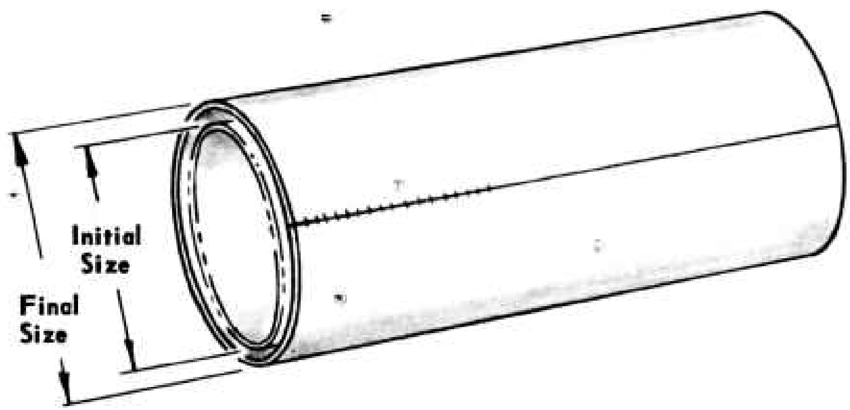


B. MODIFIED BUDD CONCEPT

FIGURE 3. EXPERIMENTAL MOTOR-CASE WELDING CONFIGURATIONS



C. RYAN CONCEPT



D. ARDE–PORTLAND CONCEPT
(Cold Expansion of Completed Cose)

FIGURE 3. (CONTINUED)

(2) deep-penetrating welds can be produced (with high-power-density equipment) that have very narrow weld and heat-affected zones, and (3) very precise control of welding variables is possible.

The narrowness of welds and heat-affected zones produced with a high-voltage-type electron-beam welder was demonstrated by Pratt and Whitney.[10] Single-pass welds were deposited in 0.095-inch-thick beta titanium by the inert-gas tungsten-arc (TIG) and the electron-beam welding process. The widths of the welds and heat-affected zones (HAZ) and the grain size of the as-deposited welds were determined from micro- and macro-examination of weld cross sections. The results are shown below.

Welding Process	Width of Weld, inch	Width of HAZ, inch	Grain Size of Weld, inch
TIG	0.375-0.438	0.140-0.180	0.035
Electron Beam	0.060	0.002	0.010-0.025

The depth-to-width ratio of the single-pass weld is much greater for the electron-beam deposit. This ratio may be as high as 20 for relatively thick material. This limited weld and HAZ size may have drawbacks. Pratt and Whitney observed that the hydrogen content of electron-beam welds in beta titanium increased with decreasing weld-bead width, apparently because of the higher solidification rate. The finer grain size of electron-beam-welded specimens as compared with TIG-welded specimens probably accounts for the improved notched tensile strengths and fracture toughness of Ti-13V-11Cr-3Al weldments evaluated by Pratt and Whitney. This smaller grain size seemingly does not improve bend or tensile ductility.

Electron-beam welders also have been used by MIT[11] for preheating and outgassing of steels preparatory to electron-beam welding. They used a diffuse electron beam to locally preheat and outgass the immediate vicinity of the weld joint. The Alloyd Corporation[12] used the electron beam for localized postheating and aging of welds after welding. Electron-beam welds were deposited with a low-voltage-type welder in various titanium alloys. The welds and HAZ's were aged by making several passes with the electron beam. Lower voltage, amperage, and travel speeds were used in these aging passes. Temperature measurements were made of various regions of the weld during the aging treatment. They found that a peak postheat temperature of 1600 F was the minimum practical temperature to effect aging in the 1/8-inch-thick titanium alloys. They point out that these alloys normally are aged at 800 to 1000 F for relatively long periods of time, but the high-temperature short-time aging afforded by the electron beam imparts the same total energy input.

High-frequency resistance welding is another new welding tool that offers promise for fabricators of rocket-motor cases. This process has been used successfully in the production of butt-welded pipe. Basically, the process consists of forcing together the moving edges of the plates to be joined at the same time that the edges are heated to the welding temperature by high-frequency current. The welding current is introduced into the metal by contact shoes strategically located in relation to the joint. The current flows along low-inductance paths and near the surface of the metal. The depth of heating usually is very shallow, and molten metal is squeezed from the weld. The process seems ideally suited to making longitudinal seams in large-diameter motor cases.

CONVENTIONAL WELDING PROCESSES AND PROCEDURES

The previous sections of this report have been concerned with new developments in rocket-motor case fabrication. It was mentioned earlier that this report would update DMIC Memorandum 56, "Welded Fabrication of Solid-Fuel, Rocket-Motor Cases". Much of the information concerning conventional welding processes and procedures contained in that previous report is still applicable. For completeness, this section will duplicate the information in the previous publication, with modifications as required.

Weld-Joint Design

The principal weld in current large rocket-motor cases, formed by shear spinning, deep drawing, or machining from forgings, is the circumferential joint joining cylindrical sections or joining spline-joint rings to cylinders. These joints are less critical than the longitudinal seams because of their favorable orientation with respect to the major stresses. Nevertheless, they require good welding procedures. The actual joint design is dictated by the thickness of the sheets to be joined and by the type of base plate and filler metal used. Usually, a square-butt joint is used for materials up to about 0.100 inch thick. Single-vee joints usually are used in thicknesses from 0.100 inch to about 1/4 inch. Double-beveled joints are used where possible for plate thicknesses exceeding 1/4 inch to minimize distortion from uneven welding. The included angle of the groove usually is 90 degrees for the thinner sheets, but is decreased to about 60 or 70 degrees for thicknesses around 3/16 to 1/4 inch.

The weld-joint design largely controls the amount of dilution of the filler wire with the base material. Very little filler metal is added to square-butt joints, so the resulting weld metal will have an analysis very close to that of the base plate, even though the filler-wire composition is dissimilar to that of the base plate. However, in the case of beveled joints, the composition of the filler wire becomes of considerable importance. In this case, the filler wire may represent a substantial portion of the total weld-metal content and so will greatly affect the weld-metal composition. The effects of filler-wire composition on weldment performance is discussed in the next section.

Other factors that may influence the choice of weld-joint design are the type of shielding gas used (e.g., argon or helium) and the type of welding fixture that is used.

Filler-Wire Composition

The composition of the filler wires used to join high-strength materials is very important. Weldment strength and hot-cracking susceptibility depend greatly on filler-wire composition. Most fabricators prefer to match the filler-wire composition with that of the base plate, where possible, for uniform weld and base-plate response to heat treatment. In some instances, fabricators prefer "undermatching". That is, the filler-wire composition is selected so that the strength of the deposited weld will be less than the strength of the base plate. The use of "undermatching" presupposes that the weldment is exposed to a proper stress environment. For example, tension tests of transverse weld specimens containing low-strength filler metal fail in the weld at the

strength level of the filler material, and virtually all of the elongation occurs in the weld. On the other hand, tension tests of longitudinal weld specimens containing the same low-strength filler metal fail at the strength level of the base plate. The weld metal and base plate must elongate equally. The low-strength filler metal merely yields at its normal stress level and begins to strain plastically before the base plate is strained to the elastic limit. Composite straining continues until the fracture strength of the base plate is reached. Since the circumferential-longitudinal stress ratio in a long, thin-wall cylinder is 2:1, it is reasonable to believe that low-strength filler metals would perform satisfactorily in the girth welds of rocket-motor cases. Some fabricators actually have used lower strength filler metals for these girth welds with apparently satisfactory results.

The tramp-element content of filler wires is very important to hot-cracking sensitivity. The results of considerable research[13-16] have shown that tramp elements such as sulfur and phosphorus promote hot cracking in low-alloy steels such as AISI 4340. Sulfur and phosphorus form low-melting-point eutectics that segregate at the grain boundaries and interdendritic regions during cooling from the molten state. These eutectics form as films in the grain boundaries and can remain molten to relatively low temperatures. Shrinkage and/or external forces can separate the grains at these liquid-film boundaries. Limiting sulfur and phosphorus to 0.015 per cent each, or 0.025 per cent collectively, will greatly reduce hot cracking in AISI 4340 steel.[15] Other research[16] indicates these restrictions are not stringent enough for the high-silicon-type low-alloy steels. Weld hot cracking was prevalent in a vacuum-melted, high-silicon, low-alloy steel despite sulfur and phosphorus contents of 0.005 and 0.011 per cent respectively. This research showed that increasing silicon lowered elevated-temperature ductility, presumedly by promoting the microsegregation of sulfur and phosphorus to interdendritic regions of the weld. Microshrinkage cavities and microcracks formed in these interdendritic areas and substantially lowered the strength of these weldments. More significantly, these microdefects were too small to be detected radiographically. At relatively low-strength levels (below about 200,000 psi yield strength), these defects probably can be tolerated. At higher strength levels, they are potentially dangerous. The permissible or critical size of defect that can cause failure is an inverse function of the strength and fracture-propagation characteristics of the material. As the length of the defect increases, the load necessary to develop fast fracture failure decreases. Similarly, the safe load-carrying capacity of a structure is decreased when the structure is fabricated from a material with poor resistance to fast fracture propagation. Consequently, attention to apparent minor defects becomes extremely important as the strength level of the material is increased.

Fixturing

Fixturing is a very important factor in the successful production of rocket-motor cases. The materials used to produce the shell of large motor cases are so thin that fixturing is mandatory for good weld-joint control. The type of fixture usually used in fabricating rocket-motor cases is the hydraulic expanding fixture that goes on the inside of the case. Sufficient expansion is used to straighten out wrinkles or local out-of-roundness in the case and to bring the two parts to be joined into nearly perfect alignment. Usually, this fixture is fitted with heaters of some type to provide for preheating and postheating. Electrical resistance heaters are widely used for this operation. The complexity of the fixture depends to a great extent on the type of the case being manufactured. In many instances, the fixture must be partially assembled and disassembled within the case for subsequent removal from the reduced neck of the vessel after welding.

The case is usually mounted on rollers to rotate the entire assembly under a fixed welding head. Single-pass welds usually are deposited from outside the vessel. However, some fabricators prefer to deposit these single-pass welds from the inside of the vessel. Monitoring of the welding on the inside has been done with a television camera mounted inside the case. Butt joints in relatively thick plate often are welded from both the inside and outside of the case.

Positive "hold-down" of the parts being joined is necessary to prevent mismatch. If an inside expanding fixture is used, hold-down rings paralleling the weld should be used on the outside of the joint to prevent localized warping or "raising up" of the plate just in advance of the welding arc.

Base-Plate and Filler-Wire Cleanliness

Many of the difficulties with porosity usually can be traced to improperly cleaned base plate and filler wires. The surfaces of the base plate in the immediate vicinity of the weld joint should be thoroughly cleaned before welding. This is particularly true of welds in titanium and its alloys. Filler wires usually are carefully cleaned and thoroughly wrapped by the electrode manufacturer before shipment. Regardless, adequate precautions must be taken to insure that the filler wire is clean just before welding. Some fabricators forbid the use of copper-coated filler wire to prevent the possibility of copper's alloying with the deposited weld metal. Since the copper coating is about 0.0002 inch thick, it is very unlikely that a sufficient concentration of copper in the weld could be accumulated to cause weld cracking. If bare uncoated wires are used, they should be carefully examined to insure that no rust remains on the wire before use.

Shielding and Backup Gas

Both argon and helium as well as mixtures of the two gases have been used for shielding when using the inert-gas tungsten-arc process or the inert-gas consumable-electrode process. Helium shielding gas is preferred because of the deeper penetration and narrower weld deposits that result. Welding-grade argon (commercially pure) generally is used in preference to the mixture of argon with 2 per cent oxygen in order to minimize alloy loss from oxidation during welding.

Argon is generally used for weld backing gas. The welding fixture is provided with holes in the backup bar for the admission of a backing gas. Usually, the backup bar is recessed so that the molten metal is retained in position by positive pressure of the backing gas. Unequal backing-gas distribution that permits unusually high gas pressures to build up may produce poor underside bead contour.

Preheat and Postheat

Preheat and postheat are used for two reasons: (1) to help reduce or prevent weld-metal cracking and (2) to produce an as-deposited weld-metal microstructure of maximum ductility for ease of handling. Most rocket-motor-case welding fixtures are fitted

with heaters to provide the preheat and postheat. The postheat is usually the same temperature as the preheat. The subject of preheating and postheating is controversial.

Some fabricators use both preheating and postheating. Some use neither. Of those that use preheating and/or postheating, few agree on the optimum temperature (and time at temperature for postheating) for a given material. The ideal preheat-postheat condition in the case of low-alloy hardenable steels is one which will produce bainite rather than martensite as a product of austenite decomposition on cooling from the welding operation. This ideal thermal cycle, then, is one which arrests the cooling at a temperature which is too high for martensite to form and for a sufficiently long period for bainite to form. However, as pointed out in the American Welding Society Missiles and Rockets Welded Fabrication Committee Report(17), this ideal condition dictates a "preheat, interpass, and hold" temperature (30 minutes after welding) of 600 to 700 F (just above the M_s of the steel in question). This high temperature is objected to by welding engineers because of oxide formation during the preheating cycle. Some fabricators have attributed weld-porosity difficulties to this oxide. As a result, most fabricators compromise. That is, they use preheat and postheat temperatures of 300 to 450 F.

As previously stated, there is wide disagreement over the optimum preheat and postheat temperatures for welding various steels. In general, the lowest preheat and postheat temperatures that can be used to produce a satisfactory structure of maximum ductility is desirable.

Heat Input

Heat input is generally measured in terms of joules per inch of weld. As a rule, the lowest heat input should be used that will produce an acceptable weld profile, regardless of the welding process used. Excessive heat inputs enlarge the heat-affected zone and increase the incidence of hot cracking. The preference for helium as a shielding gas is based on its effect on heat inputs. With helium, penetration is greatly increased at a given current, and a lower net heat input can be used.

Sequence Procedure

The number of passes that are used to join comparatively thin steel sheet varies widely with the various manufacturers. For example, some fabricators use the continuous-pass technique to weld thin-walled rocket motor cases. The case is rotated continuously beneath a stationary welding head. Weld metal is deposited continuously until two complete passes have been made. This technique has the advantage of providing only one start and stop. Other manufacturers deposit two or three separate passes when welding thin materials. Some of these passes are "dry", that is, without the addition of any filler metal. During other passes, filler metal is added. The sequence of dry passes and passes where filler metal is added are varied depending on the manufacturer.

As a general rule, welds in rocket-motor cases should be made in the fewest number of passes needed to achieve weld soundness and complete penetration. Excessive welding increases the chances of weld cracking and porosity, in addition to widening the weld appreciably.

Stress Relief

Most manufacturers use a stress-relieving operation after the welding cycle has been completed. However, there is considerable disagreement as to the procedure to be followed immediately after welding and before stress relieving. For example, some manufacturers do not allow the weld to cool below the postheat temperature before stress relieving. Other manufacturers allow the weld to cool to room temperature before stress relieving. The postweld treatment that will produce the most ductile microstructure should be used. Subsequent "stress-relieving treatments" would have the effect of tempering any martensite that may have formed. The magnitude of the residual stresses that remain after stress relieving depends on the yield strength of the material at the stress-relieving temperature. Effective release of residual stresses in hot-work die steels from a 1200 F stress-relief treatment is unlikely.

Weld Inspection

One of the most important items in the fabrication of solid-fuel rocket motor cases is inspection after fabrication. As mentioned in the section entitled "Background Information", the difference between the past failures and present successes has been largely a result of better inspection and quality-control techniques.

The various inspection techniques that are used, in decreasing order of use, are (1) radiography, (2) magnetic particle, (3) dye penetrant, and (4) ultrasonic. Usually, several of the above techniques are used, one to complement the other. Each of the techniques has certain limitations. Dye-penetration techniques are limited to defects on the surface of the plate. Defect orientation is important in magnetic particle and radiographic inspection and to a somewhat lesser extent in ultrasonic inspection.

Extensive research has shown that the critical size of defect that can be tolerated before the development of fast fracture decreases as the ultimate tensile strength of the material increases. Therefore, the burden on defect detection increases as the strength of the base plate increases. Uniform standards for acceptance of defects in rocket-motor cases are not available. Many manufacturers have established their own requirements. However, the effects of various types of defects on service performance are not known exactly; for example, the effects of scattered spheroidal-shaped porosity are not known. The removal and subsequent repair welding of areas containing scattered porosity at the expense of possibly obtaining weld and heat-affected-zone cracks from the rewelding operation is certainly questionable. Much work in this area is certainly needed.

REPAIR WELDING

Repair welding is one of the main problems in the welded fabrication of large solid-propellant rocket-motor cases, and repair welding should be avoided if possible. Many

hydrotest failures of steel production cases have initiated in areas of repair welding. Much of the difficulty can be attributed to rewelding on hardened microstructures. Generally, the case material in sheet form is received in a spheroidize-annealed condition. Shrinkage forces from the initial welding usually do not produce cracks in the unaffected base plate immediately adjacent to the heat-affected zone. After the welds have cooled to room temperature, the microstructure of the welds and heat-affected zones in air-hardening steels is either martensite, tempered martensite (if stress relieved), or bainite (if suitably postheated). The shrinkage stresses imposed by rewelding are likely to crack martensitic heat-affected zones; there is less likelihood of cracking tempered martensite or bainite. So, wherever possible, rewelding should be done only when the various martensitic weld and heat-affected zones have been softened by local tempering or annealing, or when the microstructure is bainitic.

Localized preheating and postheating should be used during rewelding. Repair welds are always subjected to much higher restraint than are the initial welds. Because the possibilities of hot and cold cracking are greater, repair welds should be inspected with extreme care.

FUTURE REQUIREMENTS IN WELDED FABRICATION OF ROCKET MOTOR CASES

Great progress has been made in the welded fabrication of solid-fuel rocket-motor cases. Anticipated future needs portend even greater advancements in fabrication know-how. Motor cases, undoubtedly, will become larger. On-site fabrication is likely to increase. Fabrication of these large cases will have to combine the forming and handling capabilities of a boiler shop with the precision fabrication techniques currently used. New materials and new welding processes will become available. Uniting these future developments into practical, usable techniques will require extensive research and development. Much of this needed research is currently being done. Long-range programs are needed to meet these advanced goals.

GENERAL REMARKS

This report has described the general techniques that are used to fabricate large solid-propellant rocket-motor cases. It is apparent that the successful fabrication of cases is an exacting operation. Techniques commonly used to produce pressure vessels of plain carbon steel are not satisfactory for fabricating rocket-motor cases. Appendix A lists in outline form the many important factors that must be considered in fabricating high-strength motor cases. It is imperative that all these factors be considered in the fabrication of these cases. Overlooking a seemingly minor detail can result in hydrotest failure, as experience has shown.

Despite numerous past and present failures of solid-propellant rocket-motor cases, considerable know-how has been accumulated and sound production techniques developed. There still remain many problems to be solved by continuing research and development.

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MDR/REM/DCM:js

APPENDIX A

CHECK LIST OF IMPORTANT MATERIALS AND FABRICATION VARIABLES

APPENDIX A

CHECK LIST OF IMPORTANT MATERIALS AND FABRICATION VARIABLES

Important factors to be considered in material and process specifications for use in fabrication of welded steel solid-propellant rocket-motor cases are outlined below.

I. General Design

A. Weld types

1. Circumferential seams
2. Longitudinal seams
3. Head attachment
4. Skirt attachment
5. Port attachment
6. Other attachments

B. Thickness-contour changes

1. Gradual
2. Abrupt

C. Dimensional control

II. Material Selection

A. Base material

1. Availability
2. Mill heat treatment
3. Surface condition
   a. Surface finish
   b. Decarburization
4. Chemical composition
   a. Alloy additions
   b. Residual elements
   c. Alloy segregation
5. Mechanical properties
   a. Uniaxial tension
   b. Biaxial tension (consistent with design)
   c. Crack-propagation resistance
6. Metallurgical properties
   a. Inclusion size and distribution
   b. Heat-treatment response
   c. Metallurgical stability
   d. Decarburization control

B. Filler metal

1. Availability
2. Chemical composition
   a. Alloy additions
   b. Residual elements
3. Efficiency of alloy transfer across welding arc
4. Filler-metal cleanliness
5. Response to base-material heat treatment
6. Wire temper, cast, etc.

C. Shielding gas or flux

1. Purity
2. Moisture content

III. Weld Factors

A. Preparation for welding

1. Joint-area preparation
   a. Cleaning
   b. Joint design
2. Fixturing
   a. Alignment
   b. Adequate dimensional control
   c. Backup design
3. Weld-joint fitup
   a. Mismatch
   b. Root spacing

B. Welding

1. Welding-process selection
2. Welding conditions
   a. Number of passes
   b. Current
   c. Voltage
   d. Travel speed
   e. Gas flow
      (1) Torch
      (2) Backup
   f. Wire addition

3. Auxiliary heating
   a. Preheat temperature
   b. In-process temperature
   c. Postheating

C. Postheating

1. Postheat temperature
2. Postheat time

IV. Heat Treatment

A. As received

B. In process

C. After welding

D. Final

1. Austenitize
   a. Temperature
   b. Time
   c. Atmosphere

2. Quench
   a. Method
   b. Media

3. Temper
   a. Temperatures
   b. Time
   c. Atmosphere
   d Number of cycles

4. Control samples
   a. Size
   b. Location in furnace

V. Inspection

A. Methods

1. Techniques
2. Sensitivity
3. Time of Inspection

B. Permissible defects

1. Type
2. Size

C. Dimensional checks

VI. Repair

A. Necessity

B. Material condition

C. Techniques

D. Heat treatment after repairs

E. Inspection after repairs

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